

Synopsis of Fermilab HINS RFQ De-tuning Problem

Bob Webber, March 31, 2009

Introduction

Fermilab has procured a 325 MHz, 50 keV-2.5 MeV RFQ from ACCSYS as a part of the High Intensity Neutrino Source (HINS) program. Peter Ostroumov from Argonne National Laboratory provided the RFQ vane modulation design. ACCSYS provided the mechanical design and construction. ACCSYS had no 325 MHz power source with which to power test the structure before delivery to Fermilab.

The design operating power of the structure without beam loading is approximately 450 kW and the design spec called for 1% duty cycle operation; nominally a three-millisecond pulse at 2.5 Hz or one-millisecond pulse at 10 Hz, corresponding to ~4500 W average RF power.

Figures 1-3 are pictures of the structure and vacuum vessel.

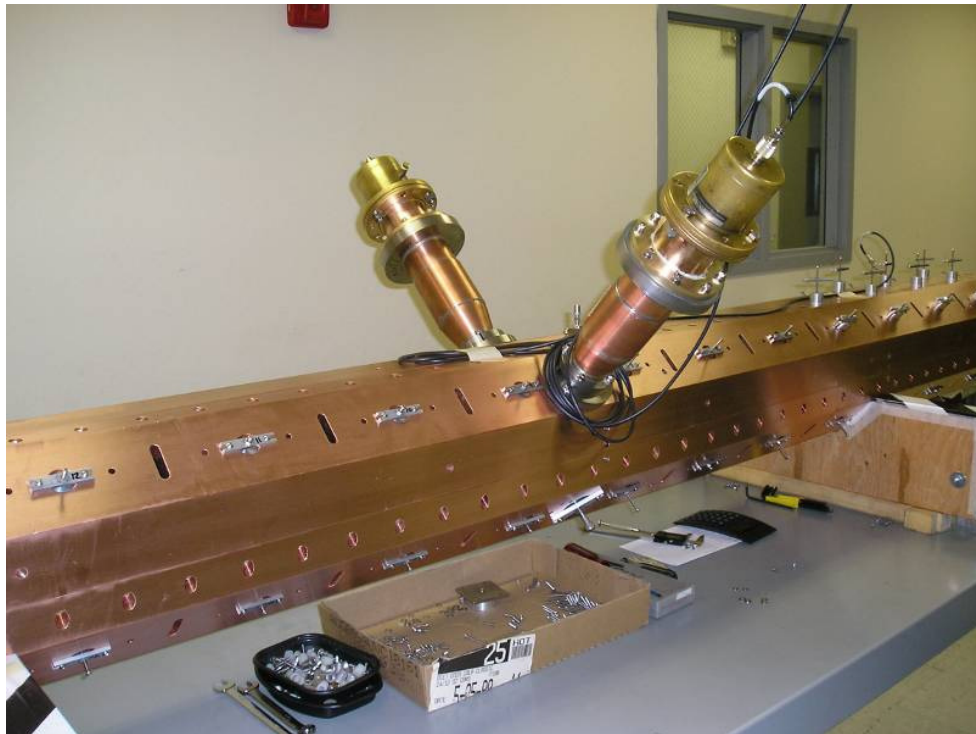


Figure 1 RFQ structure with input couplers

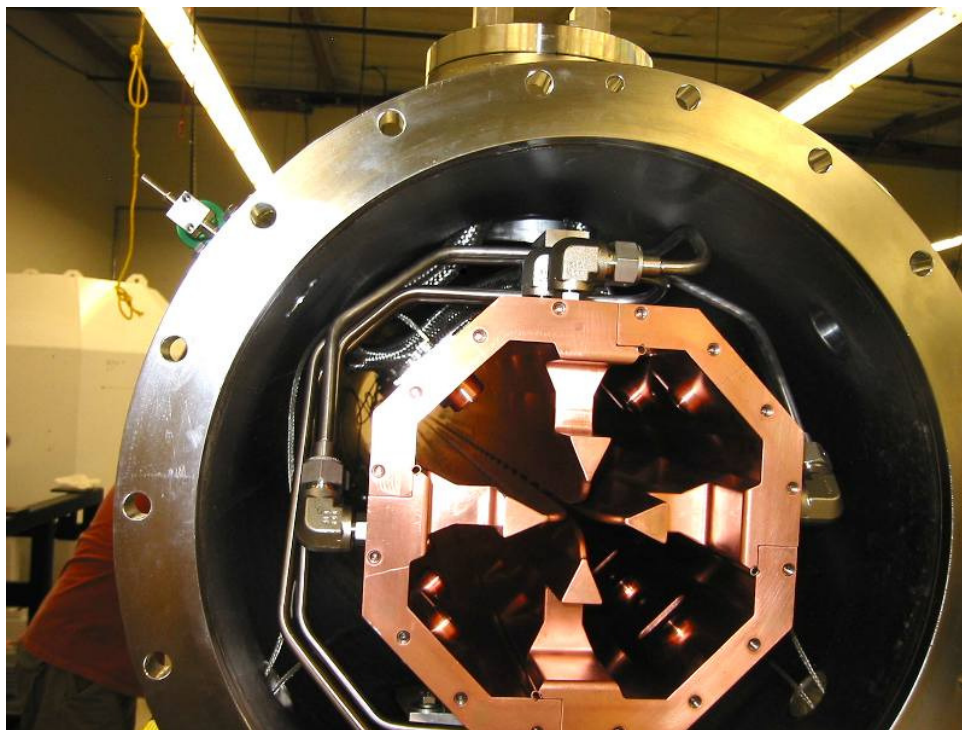


Figure 2 RFQ Structure in vacuum vessel

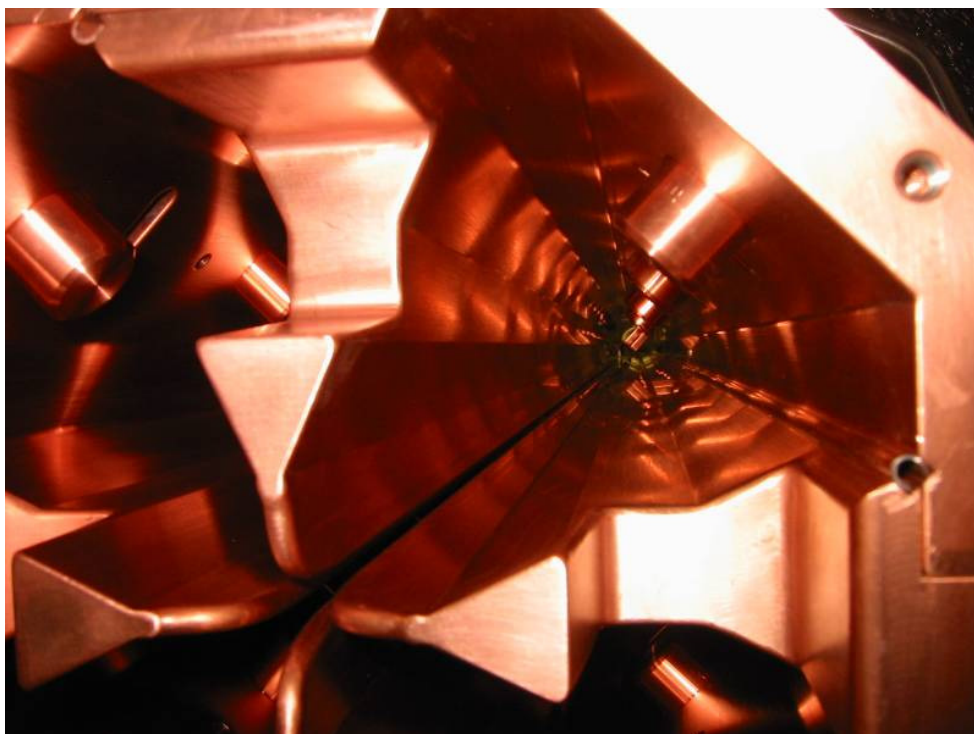


Figure 3 RFQ close-up

Installation and Initial RF Conditioning

Figure 4 shows the RFQ installation at Fermilab just before the final coaxial elbows are installed to complete RF power connections. When final connections were made for the first time a vacuum leak developed in the left-hand (as beam would see it) coupler. Fermilab personnel removed and disassembled this coupler. A leak was found on soldered joint in center conductor; it was repaired at Fermilab by re-soldering.

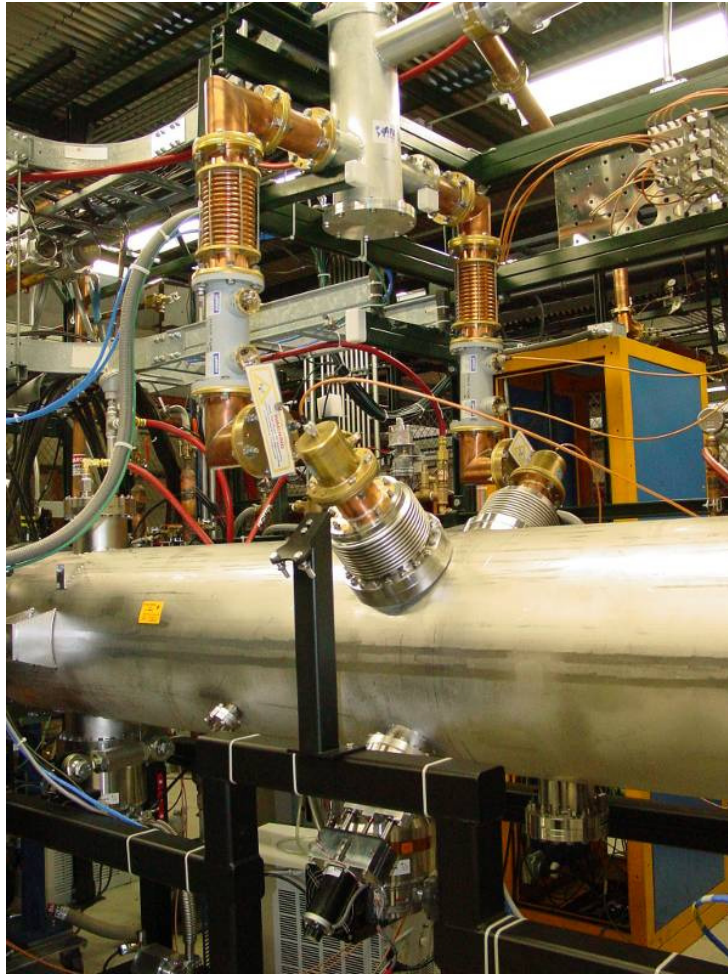


Figure 4 RFQ installation before connection of final coax elbows

A vacuum of $\sim 1\text{E-}7$ torr was achieved and RF conditioning then began, starting at low peak power and ~ 100 microsecond RF pulse length. As vacuum permitted, the pulse length was extended up to three milliseconds; then the pulse length was reduced to 100 usec and the power level incremented. This process was iterated until it became clear from reflected power coupler signals that considerable multi-

pacting and sparking was occurring, particularly in the right-hand (as seen by beam) input coupler. The sparking was detectable by an ultrasonic audio listening device.

Both couplers were removed, inspected, and leak checked. The surfaces of the loop straps on the ends of both couplers showed signs of considerable corona activity. The solder joints joining the loop straps to the coaxial structure of the coupler showed noticeable pitting on both couplers. The ceramic of the right-hand coupler was coated with a grey material that could be cleaned off with alcohol. Another vacuum leak was found in the left-hand coupler at the same location that had been previously repaired.

The loop straps were removed from both couplers to permit hi-pot of the ceramics. The right-hand coupler ceramic broke down at about 8 kV; the left-hand coupler withstood the maximum 12 kV available from the tester that was used. After thorough cleaning both couplers hi-potted good up to 12 kV. The vacuum leak was again repaired on the left-hand coupler. To re-attach the loop straps, a decision was made to remove old solder and weld the straps to the coaxial coupler structures.

The couplers were re-installed on the RFQ. A vacuum of better than 5×10^{-8} torr was obtained and RF conditioning began again following the same iterative process as before.

After approximately two weeks (ten eight-hour days) of conditioning, short-pulse operation at 450 kW was achieved. Work to extend the pulse length at that power level continued. During all of this conditioning time, there was no active tuning of the cavity resonant frequency. The RF generator frequency was changed manually to compensate for any tuning variations. The resonant frequency was typically 325.065 MHz (with the mechanical tuner fixed at the lowest frequency limit position).

As the average power applied to the structure increased, a new phenomenon appeared. After some minutes of stable operation following a cold start, the resonant frequency of the structure begins to shift rapidly, faster than a finger on the generator frequency control can track, and the vacuum deteriorates. There is some evidence that the initial onset of this phenomenon occurred as a singular event during a period of stable running at around 3.3 kW average power. In any case, the resonant frequency 'run-away' characteristic is now a repeatable effect for any average power level above 200-300 watts. We are now working to understand and correct this problem.

Operating Environment and De-tuning Observations and Tests

Operating Environment

We now operate with an active frequency feedback loop (not an active RFQ tuning loop). The loop maintains the phase between a forward power coupler signal and an RFQ field probe signal at a fixed value by automatically adjusting the generator frequency. This forces the RF drive frequency to track RFQ resonant frequency variations. We also have the option to operate with a pulse-to-pulse klystron forward power regulation loop.

Figure 5 is a cross-section of the RFQ showing the location of the twelve cooling-water channels running the length of the structure. We operate with two water circuits external to the RFQ; one including the

four vane channels in parallel and one including the eight body channels in parallel. Typical measured flow is 5.2 gpm in the vane circuit and 5.9 in the body circuit. Nominal water system supply temperature is 92-93° F. The vane circuit includes a 6 kW cartridge-type water heater to facilitate differential vane-to-body inlet water temperature for resonance control. The heater was de-energized during all of the tests described in this note.

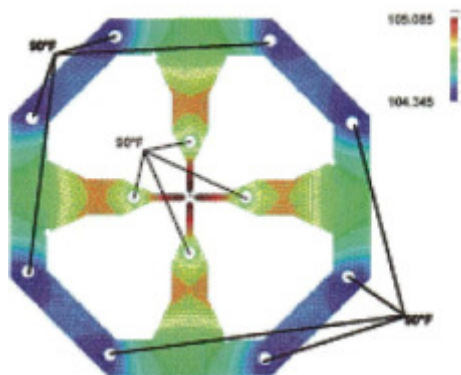


Figure 5 RFQ Cross-section showing twelve cooling-water channels

The baseline RFQ vacuum without RF power is now typically 1-2E-8 torr. RF operation below the 200-300 watt average power level is regularly done with the vacuum pressure holding around 1E-7 torr. Interlocks, with ~10 millisecond response, will trip RF power if vacuum reaches or exceeds 1E-6 torr.

Reflected power interlocks trip RF power within five microseconds when an unexpected level of reverse power is detected.

De-tuning Observations

The general character of the problem is shown in Figure 6. The full time scale of the plot in that figure is twenty minutes. RF power turns on at about the -15 minute mark. The dark red trace at the bottom of the plot is RFQ reflected power, which is very low throughout the plot indicating that the frequency-tracking loop is working as expected. The spike at -10.5 min is due to a few-pulse multipactor or sparking event. The blue trace is the RFQ cooling water inlet temperature; full scale is 10° F, so the total variation is <1°. The aqua trace with two discrete steps is the RF pulse length, starting at 0.25 milliseconds, set to one msec just prior to RF turn-on, and then to 1.5 msec shortly after RF turn-on. The yellow-orange trace, at a steady level throughout, is the pulse repetition rate at 2 Hz. The purple trace is the vacuum pressure as read by an ion gauge on the RFQ vacuum vessel; this is on a log scale with limits of 1E-9 to 1E-6 torr. The green trace is RF forward power on a scale of zero to 600kW; the operating power for this particular run was around 300 kW. Average power during the interval from -14 min to -2 min on this plot was ~450 watts (300kW peak, 1.5 msec, 2 Hz). The red trace is the RF generator frequency, 80 kHz full scale, which is tracking the RFQ resonant frequency.

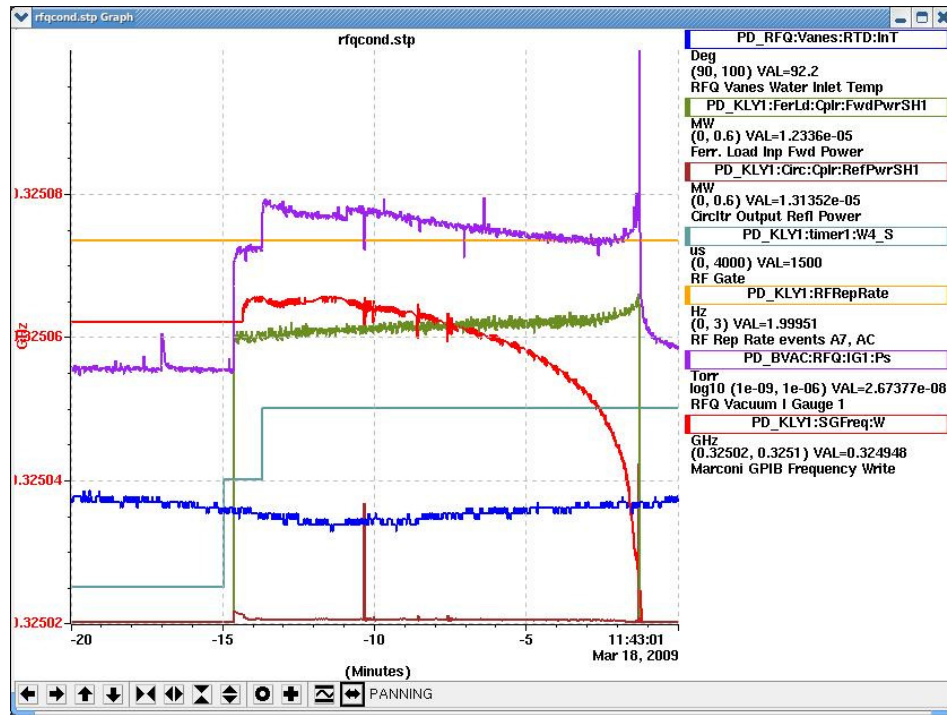


Figure 6 Typical progression to resonant frequency 'run-away'

At this 450 kW power level, the frequency changes slowly for the first ten minutes of operation, but then begins to 'run away' at an ever-increasing rate. The vacuum pressure is 2×10^{-8} before RF power turn-on, jumps to $\sim 10^{-7}$ at turn-on, then slightly higher when the pulse is increased to 1.5 msec, then slowly improves until quickly deteriorating as the frequency runs away and finally spikes to 10^{-6} at which level it trips the RF power source. The forward power slope, up to a maximum $\sim 10\%$ effect, is believed due to the klystron gain frequency sensitivity. Subsequent tests with an amplitude loop operational confirm that this relatively small variation of power is not a confounding factor to the run-away effect. The mystery is what might cause the frequency run-away.

Further Tests and Observations

Tests have confirmed that the relevant factor for reaching the run-away condition is average power. We have operated at various pulse lengths and peak powers, but average power determines the time from RF turn-on until meeting the run-away condition.

The time for the RFQ to fully recover from run-away is the order of twenty-five minutes without RF power.

We have powered the RFQ through each input coupler separately and determined that it is average RF power in the RFQ structure, not through an input coupler, that causes run-away.

We have looked quickly, although not exhaustively, at the individual RFQ field probes in the different quadrants of the structure. Initial indications show no change at the 5-10% level in relative field probe signal amplitudes from a time prior to run-away to a time during run-away.

Figure 7 is a plot of frequency (aqua) and pulsed RF power (green) for two running periods. During the time interval -80 to -65 min the RFQ is powered under normal conditions as described above with an amplitude feedback loop activated. Similar performance to that shown in the previous figure is seen; the resonant frequency changes only slowly during the first ten minutes of operation and then drops precipitously. The run-away is accompanied by vacuum activity (not shown on the plot) and fast reverse-power trips foreshortening most pulses and confusing the amplitude loop after the run-away begins.

The second interval of operation in Figure 7, between -20 and -5 min, is with identical conditions except that water flow through the vane channels is cut off. This test was to eliminate any thermal asymmetry that might be present if one or more of the parallel vane cooling channels is obstructed. In this run, the frequency immediately begins to drop at a noticeable, but decelerating rate; this is what should be expected as the vanes are heated by RF power and asymptotically approach a new thermal equilibrium. Nevertheless, after a little more than ten minutes the run-away effect takes front stage, much as it does with normal vane cooling flow. This suggests that the run-away is not due to asymmetrical vane cooling problems.

Figure 8 plot is an over-lapping continuation of that in Figure 7; the first running interval in Figure 8 is identically that of the second running interval of Figure 7. The second running interval in Figure 8 from -20 to -5 min, is for the same conditions as in Figure 7 except that now the vane water flow is restored and the body flow is cut off. In this case the frequency shows an initial positive slope before the typical run-away after about 10 minutes.

For all runs in Figures 7 and 8, the peak power is about 350 kW, the pulse length is 1 msec, and the rep rate is 2 Hz, yielding an average power of ~700 watts.

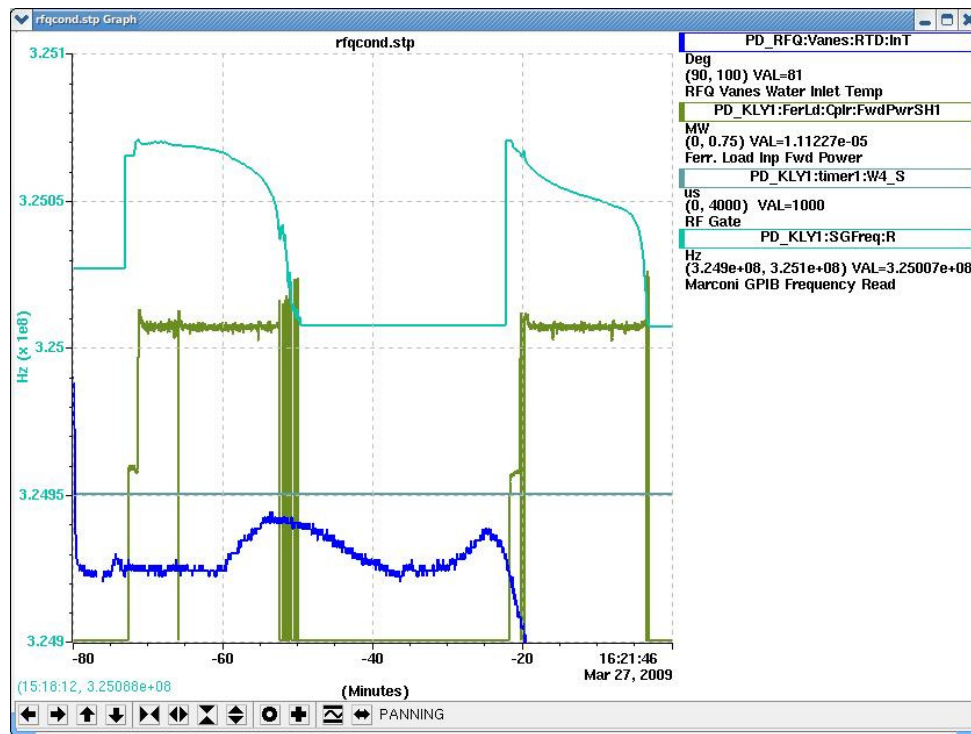


Figure 7 “Normal” cooling flow (-75 to -50 min); no vane cooling flow (-22 to -5 min) [aqua – resonant frequency, green – RF power]

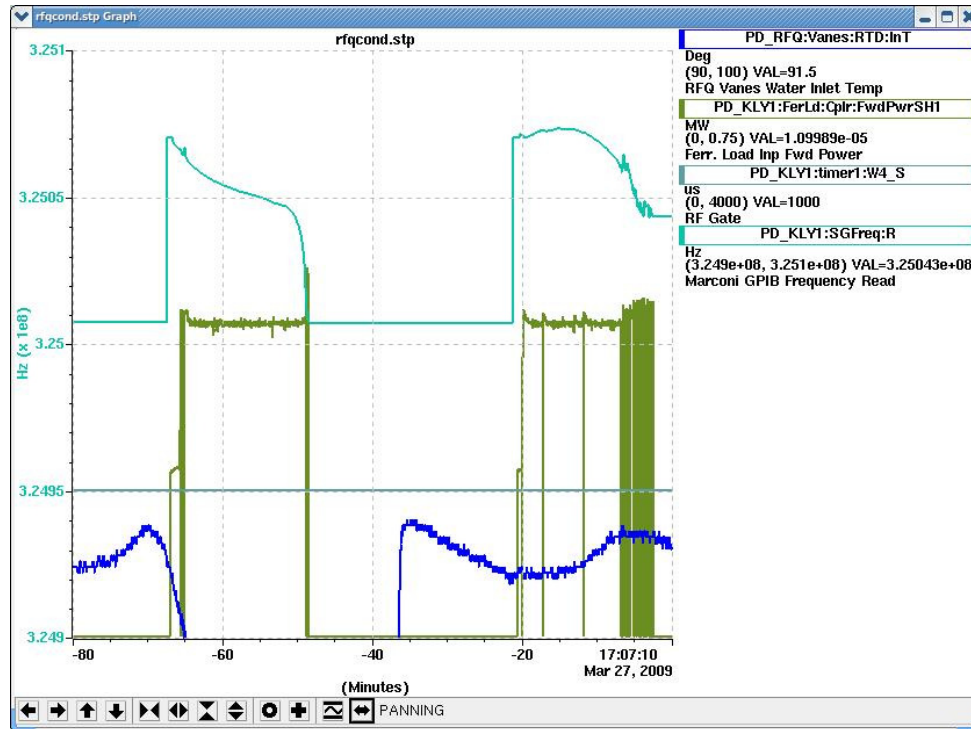


Figure 8 No body cooling flow (-22 to 0 min) [aqua – resonant frequency, green – RF power]

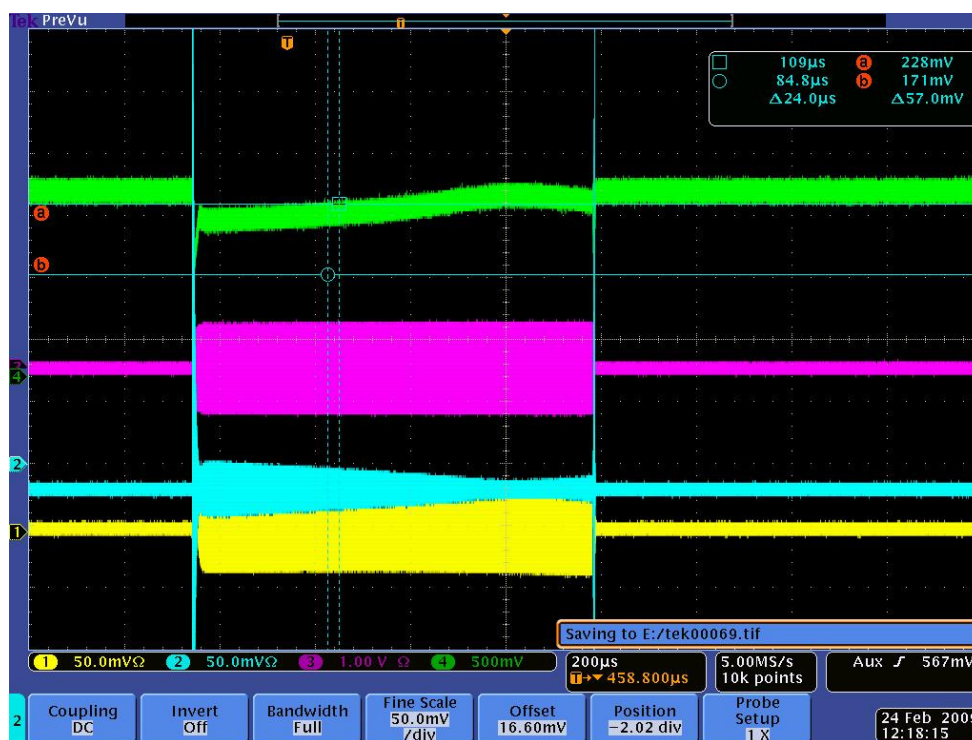


Figure 9 Green – detected reverse power, pink – RFQ field probe, blue and yellow – right and left input reverse power signals

Figure 9 is a scope screen capture showing indications of reflected power variation during a one-millisecond pulse.

In summary:

The resonant frequency run-away condition takes some time to develop after a ‘cold start’. The problem appears to be thermal; time to onset after cold-start is shorter for higher average RF power, regardless of the peak pulse power. Once the effect kicks in, there is positive feedback leading to the run-away. Whatever physical piece of the RFQ that causes the effect should be subject to RF heating and small in mass if changes observed within a one millisecond pulse are related and it must be relatively thermally isolated to be consistent with the long, few minute, time constant recovery time. The mechanism is ‘elastic’, that is, the effect is repeatable from one cold-start run to another. Separately removing either vane cooling water or body cooling water does not strongly influence the general character of the run-away behavior. Powering from either input coupler separately indicates that the problem is with the RFQ structure rather than with a coupler. Large changes in RFQ field probe signal amplitudes have not been observed to accompany the run-away.

Questions:

- 1) Has ACCSYS experienced this behavior in other RFQs?
- 2) What ideas might ACCSYS or anyone else have for mechanisms that could explain the behavior we see?
- 3) What particular tests might be conducted to pin-point the problem?
- 4) Can ACCSYS provide details of the 'RF seal' between quadrants of the structure, the C-shaped soda-straw-like piece at the longitudinal joint between uni-vane sections? (See the c-shaped piece at the structure joint on the right side of Figure 3.) What is the material? How is that seal installed and fixed in place? We suspect this may be the source of the problem.

Further Plans

We have not yet opened the structure for inspection and we have not yet attempted to accelerate beam through the structure. We anticipate opening for inspection within the next three weeks as we prepare to connect the RFQ to our ion source. We plan to try beam through the RFQ before considering any major repair activity; we can run at sufficiently high pulsed-power providing that we keep the pulse length short and the rep rate low.